NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS

TECHNICAL NOTE

No. 1639

INVESTIGATION OF SOME FACTORS AFFECTING COMPARISONS OF WIND-TUNNEL AND FLIGHT MEASUREMENTS OF MAXIMUM LIFT COEFFICIENTS FOR A FIGHTER-TYPE AIRPLANE

By Don D. Davis, Jr., and Harold H. Sweberg

Langley Memorial Aeronautical Laboratory
Langley Field, Va.

Washington

June 1948

NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS

TECHNICAL NOTE NO. 1639

INVESTIGATION OF SOME FACTORS AFFECTING COMPARISONS OF WIND-TUNNEL AND FLIGHT MEASUREMENTS OF MAXIMUM LIFT COEFFICIENTS FOR A FIGHTER-TYPE AIRPLANE

By Don D. Davis, Jr., and Harold H. Sweberg

SUMMARY

A full-scale-tunnel investigation was conducted to study the effects of time rate of change of angle of attack, idling propeller operation, and Reynolds number on the maximum lift coefficient of a single-engine fighter-type airplane. Flight test measurements of the maximum lift coefficient of the same airplane were also made and the results have been compared with the wind-tunnel data. This comparison showed exact agreement in the flaps-up configuration. In connection with the flight comparison two unusual corrections, one for a spanwise variation of the dynamic pressure and the other for the chordwise variation of the jet-boundary induced downwash, were found necessary because of a combination of two factors: the large size of this airplane compared with the wind-tunnel jet area and the high maximum lift coefficient attained by this airplane with the flaps extended. These corrections are discussed and their magnitudes are given.

The results of this investigation indicated that good agreement between wind-tunnel and flight test values of the maximum lift coefficient can be obtained if both the wind-tunnel and flight tests are carefully controlled so that such conditions as time rate of change of angle of attack, propeller operation, Reynolds number, and surface roughness are reproduced and if the airplane being tested is not too large in comparison with the size of the wind tunnel used.

INTRODUCTION

Data obtained in the Langley full-scale tunnel frequently provide opportunities to compare wind-tunnel test results with flight test results because a production airplane can be tested therein at large Reynolds numbers. Because of the importance of the landing performance of an airplane, the maximum-lift-coefficient comparison has received much attention. A previous investigation (reference 1) showed that good agreement could be obtained between the full-scale-tunnel and flight measurements of the maximum lift coefficient of an airplane, only if both the wind-tunnel and flight tests were carefully controlled and, in particular, only if the time rate of change of the angle of attack was the same for each. Both the wind-tunnel and flight tests were made with the propeller stopped. Most of the recent airplane investigations conducted in the Langley full-scale tunnel have been made for the purpose of drag clean-up and consequently only a few static determinations of the maximum lift are available for most of the airplanes investigated. These determinations have been summarized and analyzed in reference 2. The maximum lift coefficients of these investigations, when compared with the values obtained from flight tests made under various conditions, have shown large discrepancies. These discrepancies are perhaps to be expected, since in the flight tests both the time rate of change of angle of attack and the propeller operating conditions were different than in the wind-tunnel tests. Some appreciable differences were noted among the flight tests presumably for the same reason, that is, variation of test conditions.

Corrections for these differences in test conditions could not be accurately determined for at least two reasons: first, in the absence of wind-tunnel data at the proper propeller operating conditions, an accurate estimate of the effect of the idling propeller on the maximum lift coefficient was impossible; and second, the correction for the time rate of change of angle of attack was uncertain for many reasons such as the fact that the typical present-day fighter airplane differs in many ways from the airplane of reference 1. The present-day airplane has a wing which is larger and more highly loaded than that of the earlier airplane. The surface of the metal-covered wing, with numerous access doors and plates, is much rougher than the highly polished fabric surface which was maintained in the previous investigation. Also, the flaps with which the present-day fighter airplane is equipped increase the maximum lift coefficient and the drag coefficient to values far above those encountered in the earlier tests. In view of these differences in design and construction, there was some question as to the general validity of using the data of reference 1 in predicting the maximum lift coefficient of a present-day airplane. Also, available information indicated that many of the flight tests had probably been made at values of the parameter for time rate of change of angle of attack which exceeded the range of the investigation of reference 1. The extrapolation of these data was looked upon as a doubtful procedure. There was some doubt, too, as to whether the data of reference 1 would apply to the case of a wing with flaps.

The purpose of the present investigation is, therefore, to determine the effects on a present-day fighter airplane of some of the factors which, if neglected, may cause important discrepancies between wind-tunnel and flight measurements of the maximum lift coefficient and, with the aid of this information, to make a comparison of the wind-tunnel and flight measurements of the maximum lift coefficient of the airplane tested.

SYMBOLS

C_L	lift coefficient (Lift/qS)
$C_{L_{max}}$	maximum lift coefficient
$\Delta C_{L_{max}}$	increment of maximum lift coefficient
C_N	normal-force coefficient (Normal force/qS)
V/nD	propeller advance-diameter ratio
R	Reynolds number $(\rho V\bar{c}/\mu)$
q	dynamic pressure, pounds per square foot $\left(\frac{1}{2}\rho V^2\right)$
S	wing area, square feet
$\bar{c}$	wing mean aerodynamic chord, 7.8 feet
c	local wing chord, feet
b	wing span, feet
ρ	mass density of air, slugs per cubic foot
μ	coefficient of viscosity for air, pounds per foot-second
V	free-stream velocity
D	propeller diameter, feet
n	propeller rotational speed, revolutions per minute
α	angle of attack of thrust axis, degrees
$\alpha_{C_{L_{max}}}$	angle of attack at maximum lift, degrees
$\Delta\alpha_{C_{L_{max}}}$	increment of angle of attack at maximum lift, degrees
$d\alpha/dt$	time rate of change of angle of attack, degrees per second

AIRPLANE AND EQUIPMENT

The airplane used in this investigation was a single-engine low-wing fighter equipped with 0.256c and 0.64b slotted flaps which deflect to 48° in the down position. The wing sections at the root and tip were NACA 23016 and NACA 23009 airfoils, respectively. A three-view drawing showing the dimensions is given in figure 1 and a photograph of the airplane mounted in the Langley full-scale tunnel is presented as figure 2. For the present investigation the airplane was mounted as shown in this photograph except that the horizontal tail was removed for all tests and the resulting holes covered with metal fairings. The wing was in the service condition, except that the guns were removed and the gun ports were covered. The flight tests were made with the airplane wing surface covered with service camouflage paint; but in order to obtain well-defined tuft patterns for photographic studies of the air flow over the wing in the wind tunnel, the upper surface was painted white with spanwise black reference lines at the 0.4-chord and 0.7-chord stations. The surface roughness arising from the camouflage paint was not materially altered by the application of an additional coat of white paint for the tunnel tests.

A detailed description of the Langley full-scale tunnel and associated equipment is given in reference 3. For the present investigation a special tail support with high-speed gearing was used to produce a continuous change in angle of attack at rates varying from 0° to 0.85° per second. A base for use in ascertaining the time rate of change of angle of attack was provided by an NACA standard timer. The angle of attack and synchronizing signals from the tuft-study camera, the timer, and the balance print circuits were continuously recorded on film. At intervals while the airplane was moving through the range of angle of attack, the balance dials were momentarily held stationary while the readings of all the balances were printed simultaneously. In order to permit the balances to follow the rapidly varying forces and to decrease the time required for recovery following a printing impulse, a rapid balance-system response was desired. This response was obtained by reducing the damping in the balance system, which is normally heavily overdamped, to about the critical value.

METHODS AND TESTS

The investigation consisted of tuft surveys to study the air flow over the wing surface and force tests for a range of $d\alpha/dt$ from 0° to 0.85° per second. The two conditions described in the following table were investigated in detail:

Configuration	Flaps	Landing Gear	Canopy
Clean	Retracted	Retracted	Closed
Landing	Fully extended	Extended	Open

Force tests were made with the propeller idling and with the propeller removed to determine the effect of the idling propeller on the maximum lift coefficient. For the idling power conditions, the propeller was set at the low pitch stop (18° at the 0.75 radius) and was run at 350 rpm which, for a tunnel speed of 75 miles per hour, very nearly matched the flight values of V/nD. Lower propeller speeds would have been desirable for the lower tunnel speeds but were not feasible because of excessive engine fouling. Most of the tests were run at a tunnel speed of 75 miles per hour.

Some additional force tests were run with the propeller removed at velocities ranging from 38 to 75 miles per hour to determine the effect of Reynolds number on the maximum lift coefficient of the airplane. One test was made with the airplane in the landing condition but with the canopy closed to determine the effect of the canopy position on the maximum lift coefficient.

A few preliminary tests were made to determine the magnitude of the time lag and the dynamic loading in the wind-tunnel balance system caused by the continuous motion of the angle-of-attack mechanism and the test airplane. The influence of these factors was found to be negligible.

The force tests were made by first starting the timer and recorder and then printing the balance readings as the airplane moved through the range of angle of attack. The exact values of the angle of attack and the time rate of change of the angle of attack for the individual tests were determined from the galvanometer film records of the angle of attack and the time base.

In order to study the air flow over the wing surface, wool tufts, about 4 inches long, were attached to the upper surface of the wings with cellulose tape. The flow patterns ensuing with the tunnel in operation were visually observed and were simultaneously photographed by motion-picture cameras. The tufts were removed for all of the force tests.

RESULTS AND DISCUSSION

Results of the force tests showing the effects of Reynolds number, time rate of change of angle of attack, idling propeller operation, and canopy position are discussed herein. Following the results of the force tests, the results of the tuft surveys are presented and discussed with regard to the effects of the time rate of change of angle of attack on the stall progression. Typical time histories of flight stalls, which were used as a basis for comparisons of the flight values of $C_{L_{max}}$ with the tunnel data, are also presented. The flight comparison is discussed with particular attention to two unusual corrections which were found necessary because of the large size of this airplane in comparison with the size of the wind-tunnel used.

All wind-tunnel data presented have been corrected for jet-boundary and blocking effects and for support tares by the usual methods.

Force Tests

Effect of Reynolds number.- The effect of Reynolds number on $C_{L_{max}}$ is shown in figure 3 for the airplane with the propeller removed. These curves show that increasing the Reynolds number from 2.5×10^6 to 5.1×10^6 had a small effect (reference 2) on the maximum lift coefficient of the airplane as tested. Wing roughness resulting from numerous surface discontinuties caused by rivets, surface gaps, and access doors and from normal surface deterioration due to several years of use may be responsible for the small magnitude of the Reynolds number effect as indicated in reference 4.

Effect of $\frac{\bar{c}}{V}\frac{d\alpha}{dt}$.- The variations of the lift coefficient with the angle of attack for values of the nondimensional parameter for time rate of change of angle of attack $\frac{\bar{c}}{V}\frac{d\alpha}{dt}$ ranging from 0 to 0.063 are presented in figure 4 for the propeller-removed configuration. In the clean condition $C_{L_{max}}$ increases from 1.15 to 1.21 as $\frac{\bar{c}}{V}\frac{d\alpha}{dt}$ increases from 0 to 0.061 (fig. 4(a)); whereas in the landing condition the increase in $C_{L_{max}}$ is from 1.63 to 1.72 as $\frac{\bar{c}}{V}\frac{d\alpha}{dt}$ increases from 0 to 0.063 (fig. 4(b)).

A summary of the data obtained during this investigation showing the increments of $C_{L_{max}}$ resulting from increasing values of $\frac{\bar{c}}{V}\frac{d\alpha}{dt}$ is given in figure 5. The range of values for this parameter was increased beyond that of figure 4 by decreasing the test velocity. A value of $\Delta C_{L_{max}}$ of about 0.13 was obtained when $\frac{\bar{c}}{V}\frac{d\alpha}{dt}$ was increased from 0 to 0.12. The position of the flaps and the landing gear had little effect on the variation of $\Delta C_{L_{max}}$ with $\frac{\bar{c}}{V}\frac{d\alpha}{dt}$. The effect of increasing the parameter $\frac{\bar{c}}{V}\frac{d\alpha}{dt}$ on the increment of angle of attack for $C_{L_{max}}$ is given in figure 6 for the same conditions as in figure 5. Although the test points scatter considerably, the results show a definite increase in the angle of attack for $C_{L_{max}}$ with increasing $\frac{\bar{c}}{V}\frac{d\alpha}{dt}$. The data for the propeller-removed conditions show larger increments in the angle of attack for $C_{L_{max}}$ in the clean condition than in the landing condition.

In the investigation of reference 1, which is the most recent similar investigation, the range of $\frac{\bar{c}}{V}\frac{d\alpha}{dt}$ was only about 0.1 of that for the present investigation. Over this small range the maximum-lift-coefficient increments were much greater than those measured in the present investigation. Moreover, because of the limited test range the large decrease in slope for the curve of $\Delta C_{L_{max}}$ against $\frac{\bar{c}}{V}\frac{d\alpha}{dt}$ at the higher values shown in figure 5 was not reached. The difference in the values of $\Delta C_{L_{max}}$ obtained in the range where the test results overlap probably results from the numerous differences in the two airplanes tested. In particular, the earlier tests were conducted with an airplane having a smooth rectangular parasol wing of $2R_1 12$ airfoil sections in contrast with the comparatively rough, tapered (2:1), low wing of NACA 230-series airfoil sections used on the airplane tested in the present investigation. The increase in maximum lift coefficient due to the time rate of change of angle of attack is the result of a delay in the separation of the flow over the wing as shown in the section entitled "Tuft Studies." The factors of wing-surface roughness, taper ratio, airfoil section characteristics, and wing-fuselage interference are known to have a strong influence on the progress of the flow separation over a wing for static conditions. It is logical that these factors should also have an important influence on the progress of flow separation under conditions of changing angle of attack. It is probable also that data obtained in this investigation are not quantitatively applicable to all other airplanes although the data indicate the order of magnitude of the effect of $\frac{\bar{c}}{V}\frac{d\alpha}{dt}$ on $C_{L_{max}}$. From these results, it appears that a careful estimate of flight values of $C_{L_{max}}$ from wind-tunnel data or comparisons of flight values of $C_{L_{max}}$ with one another must include careful consideration of the effect of $\frac{\bar{c}}{V}\frac{d\alpha}{dt}$ on $C_{L_{max}}$.

Effect of idling propeller operation.- The variation of the lift coefficient with the angle of attack for values of the nondimensional parameter $\frac{\bar{c}}{V}\frac{d\alpha}{dt}$ ranging from 0 to 0.061 are presented in figure 7 for the propeller-idling configuration. A comparison of figures 4 and 7 shows the same increasing trend of $C_{L_{max}}$ and $\alpha_{C_{L_{max}}}$ with $\frac{\bar{c}}{V}\frac{d\alpha}{dt}$ for the propeller-idling condition as for the propeller-removed condition. The values of $\Delta C_{L_{max}}$ due to airplane rotation in pitch with the propeller idling are about 20 percent higher than with the propeller removed (fig. 5); this amounts to an increase in $\Delta C_{L_{max}}$ of about 0.02

at a value of $\frac{\bar{c}}{V}\frac{d\alpha}{dt}$ of 0.09. For the results with the propeller operating given in figures 5 and 6, the values of $\frac{\bar{c}}{V}\frac{d\alpha}{dt}$ above 0.06 were obtained by decreasing the tunnel velocity while the propeller rotational speed was maintained at a constant value (350 rpm). Thus the higher values of $\frac{\bar{c}}{V}\frac{d\alpha}{dt}$ were obtained at decreased values of V/nD (V/nD ranged from 1.40 to about 0.94). The variation of $\Delta C_{L_{max}}$ and $\Delta\alpha_{C_{L_{max}}}$ with $\frac{\bar{c}}{V}\frac{d\alpha}{dt}$ was not materially altered by the variation of V/nD within the range investigated. In this condition, as in the propeller-removed condition, the position of the flaps and the landing gear appears to have little effect on the varation of $\Delta C_{L_{max}}$ with $\frac{\bar{c}}{V}\frac{d\alpha}{dt}$.

Curves showing the effect of the idling propeller on $C_{L_{max}}$ and $\alpha_{C_{L_{max}}}$ are given in figures 8 and 9, respectively. Operation of the propeller at idling power $\left(\frac{V}{nD} = 1.40\right)$ resulted in an average increase in $C_{L_{max}}$ of about 0.09 for the clean configuration and of about 0.16 for the landing configuration although the propeller was operating at negative thrust. The angle of attack for $C_{L_{max}}$, however, was lower for the conditions with the propeller idling $\left(\frac{V}{nD} = 1.40\right)$ than for the conditions with the propeller removed (fig. 9) for the higher values of $\frac{\bar{c}}{V}\frac{d\alpha}{dt}$. Flight-test stalls are rarely performed at values of $\frac{\bar{c}}{V}\frac{d\alpha}{dt}$ lower than about 0.01 or rates of $d\alpha/dt$ lower than 0.1° per second.

Reducing the tunnel velocity, which also decreased V/nD, increased $C_{L_{max}}$ markedly, as is shown by the data presented in figure 10. There is a continuous increase in $C_{L_{max}}$ as V/nD is decreased such that, for the clean configuration, $C_{L_{max}}$ increases from 1.20 to 1.50 as V/nD is decreased from 1.40 to 0.70 and, for the landing configuration, $C_{L_{max}}$ increases from 1.80 to 1.88 as V/nD is decreased from 1.33 to 0.94. The importance of careful selection of the conditions of propeller operation is illustrated by the relatively large variation of V/nD with airspeed with the engine idling (throttle closed) measured in the flight tests of the present-day airplane (fig. 11).

Effect of canopy position.- The results of tests made to determine the effect of the canopy position on $C_{L_{max}}$ for the landing configuration with the propeller idling are presented in figure 12. The data show that the effect of the canopy position on $C_{L_{max}}$ is sufficiently small to be ignored for this airplane. It would be advisable, nevertheless, to test identical configurations when attempting to reproduce results of maximum lift tests on other airplanes.

Tuft Surveys

The stall progressions for the clean and for the landing configurations are shown in figures 13 and 14, respectively, for a range of values of $\frac{\bar{c}}{V}\frac{d\alpha}{dt}$ from 0 to 0.089. These sketches were drawn from visual observations and photographs of numerous wool tufts placed on the upper-wing surface. Accompanying the stall diagrams are lift curves with arrows to indicate the positions on the lift curves for which each tuft observation was made. In order to provide a rapid comparison of results, the stall diagrams for corresponding angles of attack at different values of $\frac{\bar{c}}{V}\frac{d\alpha}{dt}$ are arranged in horizontal rows.

The results of figures 13 and 14 show that for both the clean and the landing conditions the effect of increasing $\frac{\bar{c}}{V}\frac{d\alpha}{dt}$ for any given angle of attack for which partial stalling has occurred is to decrease the region of separated flow. For example, for the clean condition at an angle of attack of 17.3° (fig. 13) the wing is completely stalled for $\frac{\bar{c}}{V}\frac{d\alpha}{dt} = 0$; whereas, at a value of $\frac{\bar{c}}{V}\frac{d\alpha}{dt}$ of 0.085 most of the wing is unstalled although the flow is largely unsteady. Airplane rotation in pitch is therefore shown by figures 13 and 14 to delay the angle of attack at which separation occurs above the upper surface of the wing. These results are in qualitative agreement with the force-test results which showed increases in $\alpha_{C_{L_{max}}}$ and $C_{L_{max}}$ as the time rate of change of angle of attack was increased.

Comparison of Maximum Lift Coefficient Values in Flight Tests and in Full-Scale-Tunnel Tests

A comparison has been made of the values of $C_{L_{max}}$ obtained for the present-day airplane in the Langley full-scale tunnel and in flight. Typical time histories of stalls obtained for the test airplane in flight for the clean and for the landing configurations are given in figures 15 and 16, respectively. The flight tests were made at a Reynolds number of 6.47×10^6 for the clean condition $\left(\frac{V}{nD} = 1.20\right)$ and at a Reynolds number of 5.34×10^6 for the landing condition $\left(\frac{V}{nD} = 1.27\right)$. During the flight tests the pilots succeeded in holding both the sideslip and the bank angles to 1° or less at the time of maximum lift coefficient. The time histories of the stalls show that the airplane had sufficiently good stalling characteristics so that the maximum lift coefficient was not limited by the occurrence of any violent or uncontrollable motions of the airplane before maximum lift was reached.

The full-scale-tunnel results have been corrected to the flight values of Reynolds number, V/nD, and $\frac{\bar{c}}{V}\frac{d\alpha}{dt}$ by the data obtained in this paper. An additional correction has been applied to the full-scale-tunnel measurements of $C_{L_{max}}$ for the tail load necessary to trim the airplane at the maximum lift coefficient. This correction was derived from pitching-moment data (not presented) obtained during the present investigation. The results thus obtained showed good agreement (within 0.03) between the full-scale-tunnel values and flight values of $C_{L_{max}}$ for the clean condition. In the landing condition, however, a discrepancy of 0.19 was found between the wind-tunnel and flight results after the corrections had been made, in spite of the fact that the clean and the landing conditions had been treated by the same methods. It was known that the present-day airplane was quite large with respect to the full-scale-tunnel jet area; accordingly, a study was made of the possible effects of the large size of this airplane on the measurements of $C_{L_{max}}$ made in the wind tunnel. It was learned that the size of the airplane was such that the wind-tunnel jet was considerably distorted at high lift and drag coefficients corresponding to the landing condition although this distortion was small at low lift and drag coefficients corresponding to the clean condition. Because of this distortion two additional corrections, which are normally unnecessary, were determined and applied. The sum of these corrections was found to be of significant magnitude in the landing condition but of comparatively small magnitude for the clean condition.

The average dynamic pressure along the wing span is customarily used in reducing force data to coefficient form. The data presented herein have been obtained in this manner. Surveys made ahead of the wing in the wind tunnel revealed, however, an unusually large spanwise variation in dynamic pressure for the landing configuration at high angles of attack with the lowest dynamic pressures at the center of the wing. The normal spanwise load distribution for this airplane with flaps down shows a rather concentrated load over the central part of the wing, which was operating at a lower-than-average dynamic pressure in these wind-tunnel tests. Thus, the use of the average dynamic pressure could result in an incorrect low value of $C_{L_{max}}$. By using a value of q weighted in accordance with the spanwise load distribution, the value of $C_{L_{max}}$ for the landing condition was found to be 0.05 higher than previous calculations had indicated. For the flaps-up condition both the spanwise variation of q and the wing load distribution were more uniform; and as a result, the correction found by this procedure was negligible for that condition.

A second correction was found to arise from the influence of the jet boundary. In all wind tunnels there is a chordwise variation in the jet-boundary induced downwash. In the case of wings of small chord and wings operating at low lift coefficients this air-stream curvature produces no appreciable change in the lift characteristics. However, in the case of a wing of large chord operating at a high lift coefficient this air-stream curvature is large enough to have the effect of inducing an appreciable negative camber (in an open-throat tunnel) in the wing. Calculations showed that for the present-day airplane the effective camber change at $C_{L_{max}}$ in the landing condition was sufficient to lower the value of $C_{L_{max}}$ by about 0.05. The correction of $C_{L_{max}}$ for this effect for the clean configuration was 0.03.

Inasmuch as the previous corrections are relatively difficult and cumbersome to determine and to apply, it is recommended that in cases where accurate measurement of the value of $C_{L_{max}}$ is desired the ratio of wing area to jet area should be kept below the ratio which existed in this test (about 0.21), especially if values of $C_{L_{max}}$ of the order of 2 are expected. Since these corrections are a function of the lift coefficient, however, data obtained at values of C_L corresponding to the cruising or high-speed conditions may not be appreciably altered by these effects until the relative model size becomes somewhat larger.

A comparison of the wind-tunnel test results and the flight test results of $C_{L_{max}}$ is given in the following table:

	Clean condition	Landing condition
Corrected $C_{L_{max}}$ in tunnel	1.39	1.90
$C_{L_{max}}$ in flight	1.39	1.99

Complete agreement is shown for the clean condition.

The agreement for the landing condition, although it was considerably improved by the application of the corrections previously discussed, is not so good inasmuch as a difference of 0.09 in $C_{L_{max}}$ is indicated for this case. The explanation for this difference with the flaps deflected is not readily apparent since the excellent agreement in the clean condition tends to verify the accuracy of the methods used in this comparison. In connection with this discrepancy for the landing condition, it is interesting to compare the results of flight measurements of $C_{L_{max}}$ of the same airplane (reference 5) made one year prior to the flight tests reported herein. These earlier flight tests showed a value of $C_{L_{max}}$ of 2.20 as compared with a value of 1.99 obtained in the flight tests reported herein. This large reduction in $C_{L_{max}}$ may be due, to a great extent, to the effects of service usage on the slotted flaps used on this airplane. In reference 2 it is shown that production slotted flaps yielded increments of $C_{L_{max}}$ about 20 percent below values predicted from available two-dimensional tests of smooth slotted-flap configurations. This difference is believed to result from such items as inaccuracy of flap contour and location and roughness near the flap leading edge since the characteristics of slotted flaps are sensitive to changes in the flow conditions at this location. The flight tests reported herein were conducted about one year prior to the wind-tunnel tests. The observed loss of 0.21 in $C_{L_{max}}$ of this airplane in one year could well have been followed by some further loss in the subsequent year, thus explaining, at least in part, the 0.09 difference between the wind-tunnel test and flight test values of $C_{L_{max}}$. This 0.09 difference in $C_{L_{max}}$ is equivalent to a difference of only 2 miles per hour in the stalling speed of this airplane.

CONCLUDING REMARKS

A full-scale-tunnel investigation was conducted to study the effects of time rate of change of angle of attack, idling propeller operation, and Reynolds number on the maximum lift coefficient of a single-engine fighter-type airplane.

1. The results of this investigation indicate that good agreement between wind-tunnel and flight test values of maximum lift coefficient can be obtained if both the wind-tunnel and flight tests are carefully controlled so that such test conditions as time rate of change of angle of attack, propeller operation, Reynolds number, and surface roughness are reproduced and if the airplane being tested is not too large in comparison with the size of the wind tunnel used.

2. The comparison of the tunnel data with flight measurements of the maximum lift coefficient showed exact agreement in the clean condition. The tunnel value was 0.09 less than the flight value in the landing condition which represents a difference of only 2 miles per hour in the stalling speed. This difference is believed to result, principally, from deterioration of flap and slot details.

3. In order to avoid excessive wind-tunnel jet distortion in an open-throat tunnel, it is recommended that in cases where accurate measurement of the value of the maximum lift coefficient is desired

the ratio of wing area to jet area be lower than the ratio which prevailed in this test (about 0.21), especially if values of maximum lift coefficient of the order of 2 are expected.

4. Airplane rotation in pitch was found to delay the angle of attack at which separation occurred. For both the clean and landing conditions, increases in the maximum lift coefficient and in the angle of attack for maximum lift of the order of 0.10 and 2.5°, respectively, resulted from increases in the parameter for time rate of change of angle of attack from 0 to 0.08.

5. For the range of values of the parameter for time rate of change of angle of attack investigated, operation of the propeller at idling power (propeller advance-diameter ratio equal to 1.40) resulted in an average increase in maximum lift coefficient of about 0.09 for the clean configuration and of about 0.16 for the landing configuration.

6. Increasing the Reynolds number from 2.5×10^6 to 5.1×10^6 had a small effect on the maximum lift coefficient of the airplane as tested, presumably because of the comparatively rough wing surface of this airplane.

Langley Memorial Aeronautical Laboratory
National Advisory Committee for Aeronautics
Langley Field, Va., March 15, 1948

REFERENCES

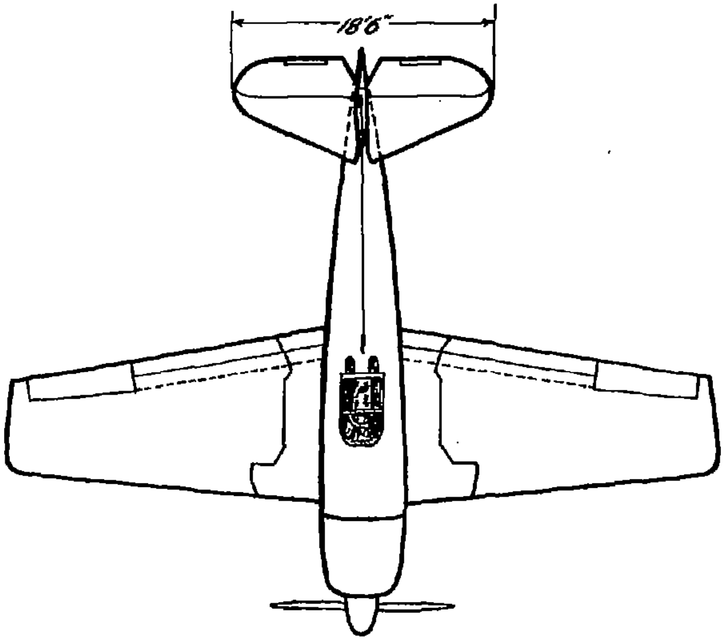
1. Silverstein, Abe, Katzoff, S., and Hootman, James A.: Comparative Flight and Full-Scale Wind-Tunnel Measurements of the Maximum Lift of an Airplane. NACA Rep. No. 618, 1938.

2. Sweberg, Harold H., and Dingeldein, Richard C.: Summary of Measurements in Langley Full-Scale Tunnel of Maximum Lift Coefficients and Stalling Characteristics of Airplanes. NACA ACR No. L5C24, 1945.

3. DeFrance, Smith J.: The N.A.C.A. Full-Scale Wind Tunnel. NACA Rep. No. 459, 1933.

4. Abbott, Ira H., von Doenhoff, Albert E., and Stivers, Louis S., Jr. Summary of Airfoil Data. NACA ACR No. L5C05, 1945.

5. Williams, Walter C., and Reeder, John P.: Flight Measurements of the Flying Qualities of an F6F-3 Airplane (BuAer No. 04776). III - Stalling Characteristics. NACA MR No. L5B13b, 1945.



Wing M.A.C., ft ---------------------- 7.8

Areas, sq ft:

Wing area (including ailerons, flaps, fuselage area)---334

Control surface areas:

Total ailerons aft of hinge line ------------15.7

Full flap area-----------------------------39.8

Total horizontal tail surface ----------------77.8

Total stabilizer area (including fuselage area and elevator balance)---------52.1

Total elevator area aft of hinge (including tabs)---25.8

Total vertical-tail-surface area--------------23.4

Fin area (including contained rudder balance)----14.4

Rudder area aft of hinge-------------------9.0

Weight, lb:

Normal weight empty-------------------8947

Normal load combat fighter---------------11,441

Normal load combat fighter with bombs----11,694

Combat fighter with overload fuel and ammunition--------------12,230

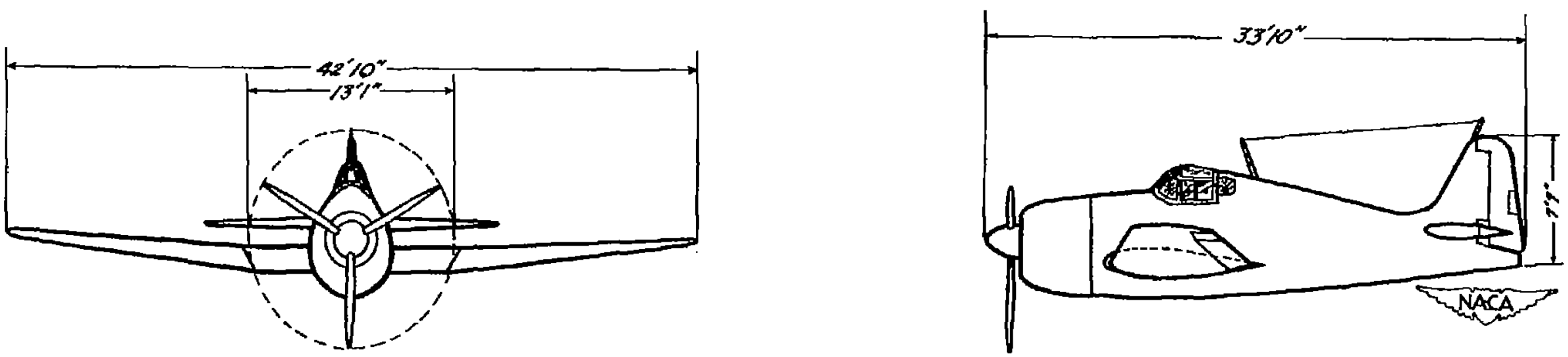


Figure 1.- Three-view drawing of fighter-type airplane.

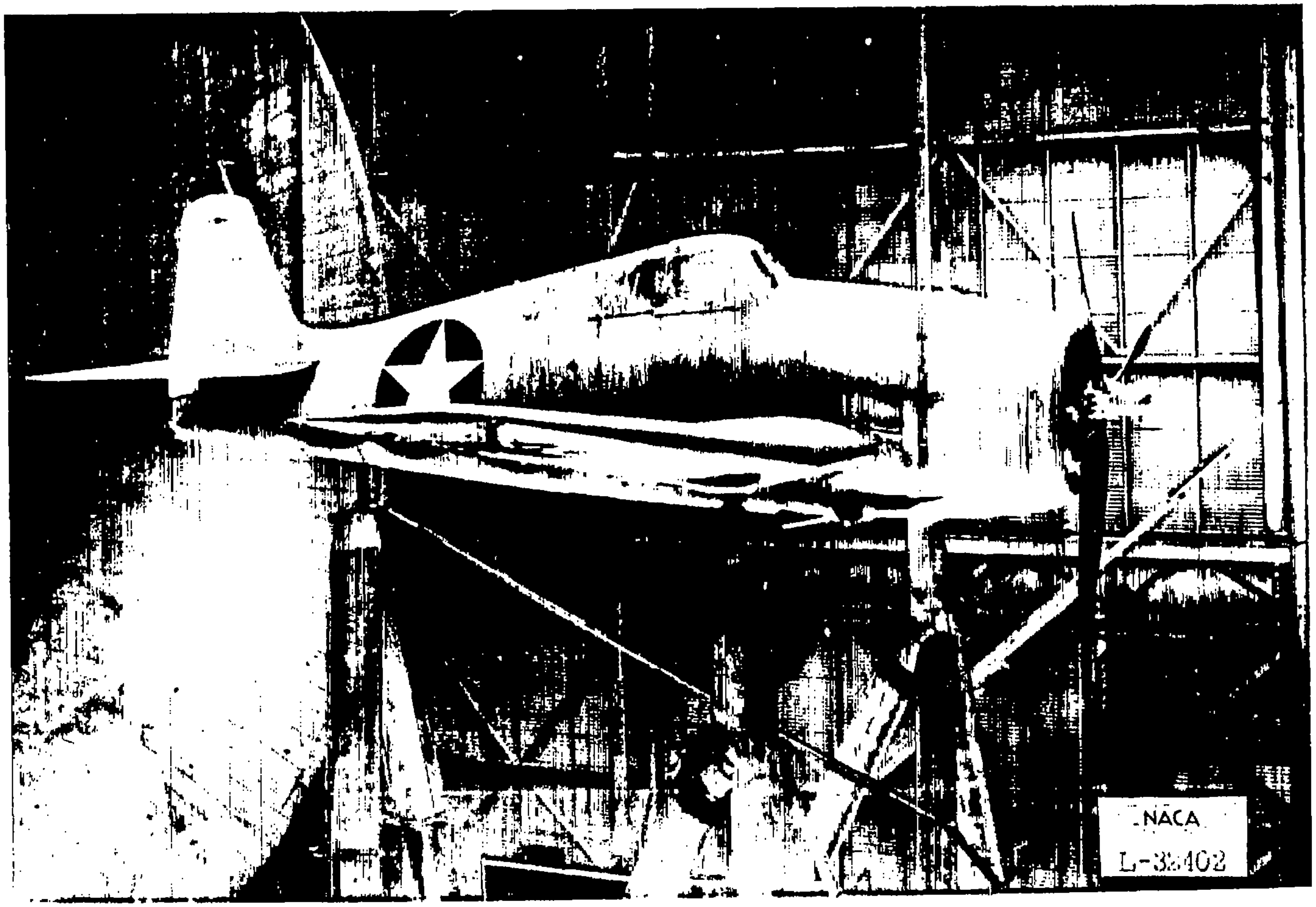


Figure 2.- Fighter-type airplane mounted in Langley full-scale tunnel.

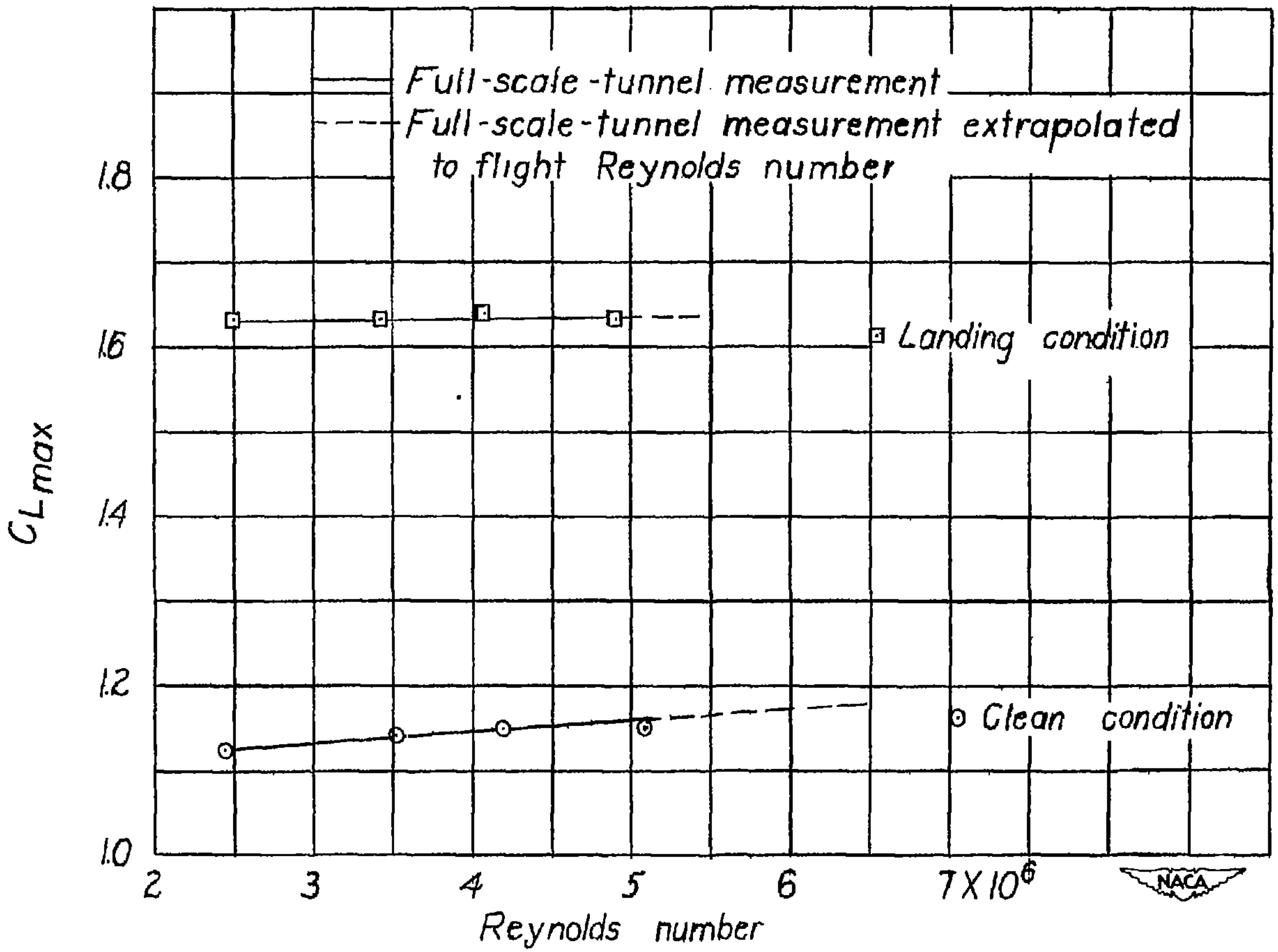
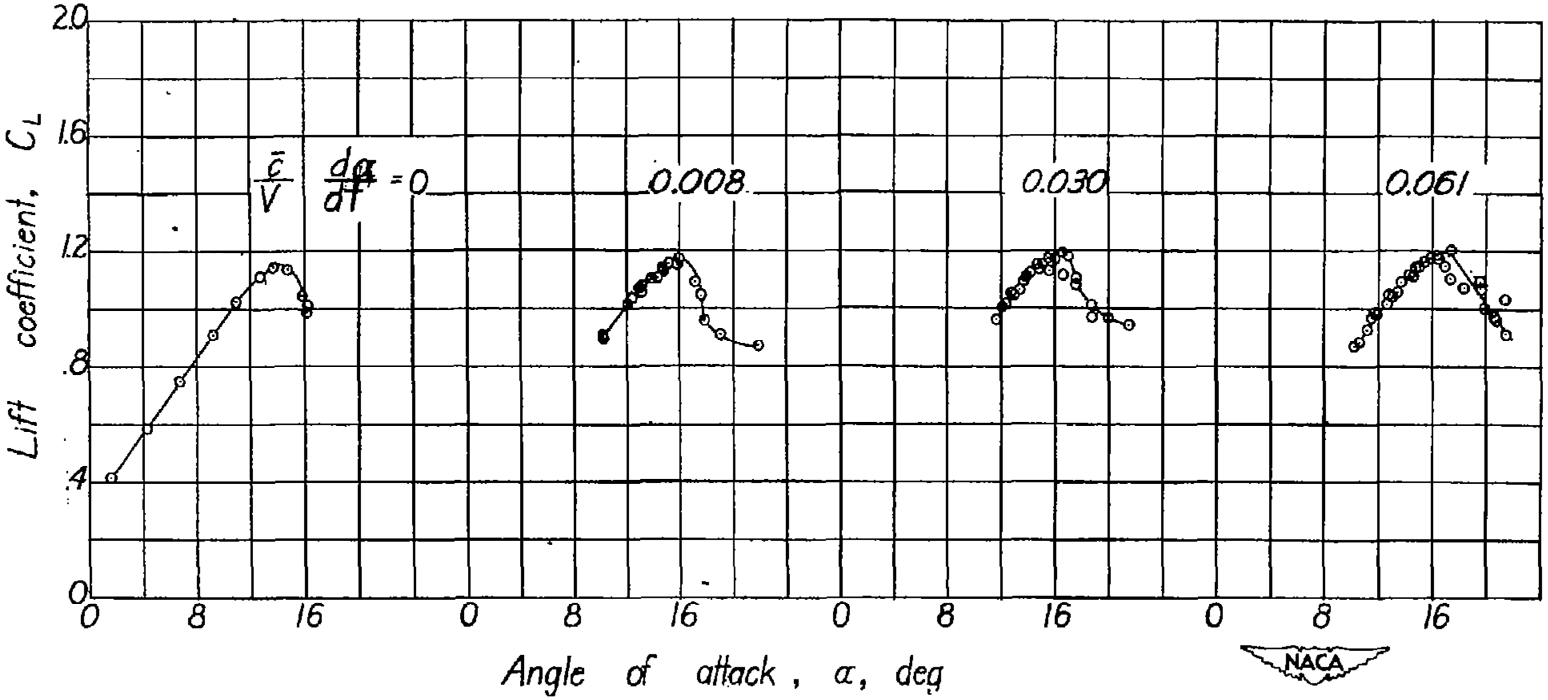
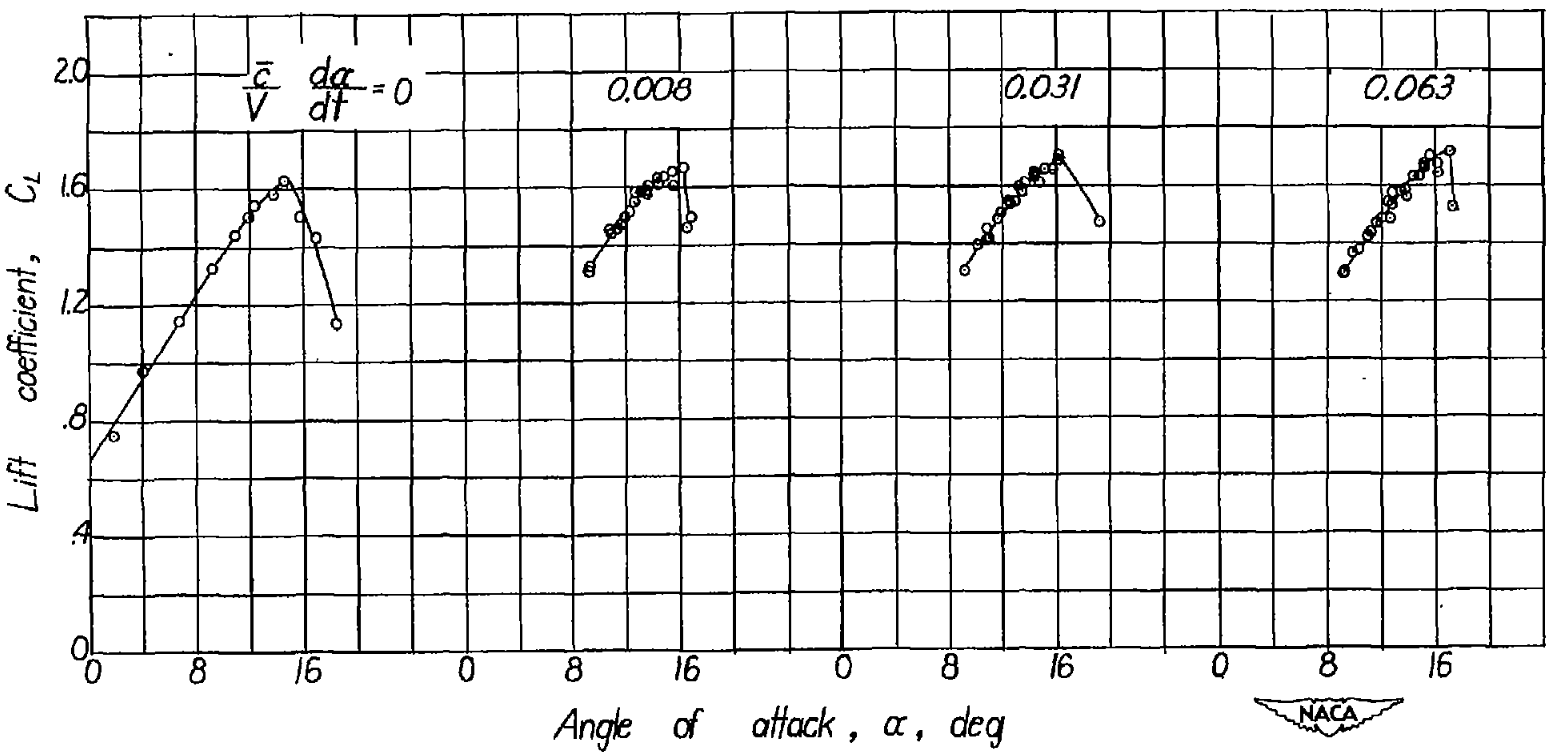


Figure 3.- Effect of Reynolds number on the maximum lift coefficient of the fighter-type airplane. Propeller removed; $\frac{\bar{c}}{V}\frac{d\alpha}{dt} = 0$.



(a) Flaps and landing gear retracted; canopy closed.

Figure 4.- Effect of $\frac{\bar{c}}{V}\frac{d\alpha}{dt}$ on the lift characteristics of the fighter-type airplane. Propeller removed; airspeed, 74 miles per hour.



(b) Flaps and landing gear extended; canopy open.

Figure 4.- Concluded.

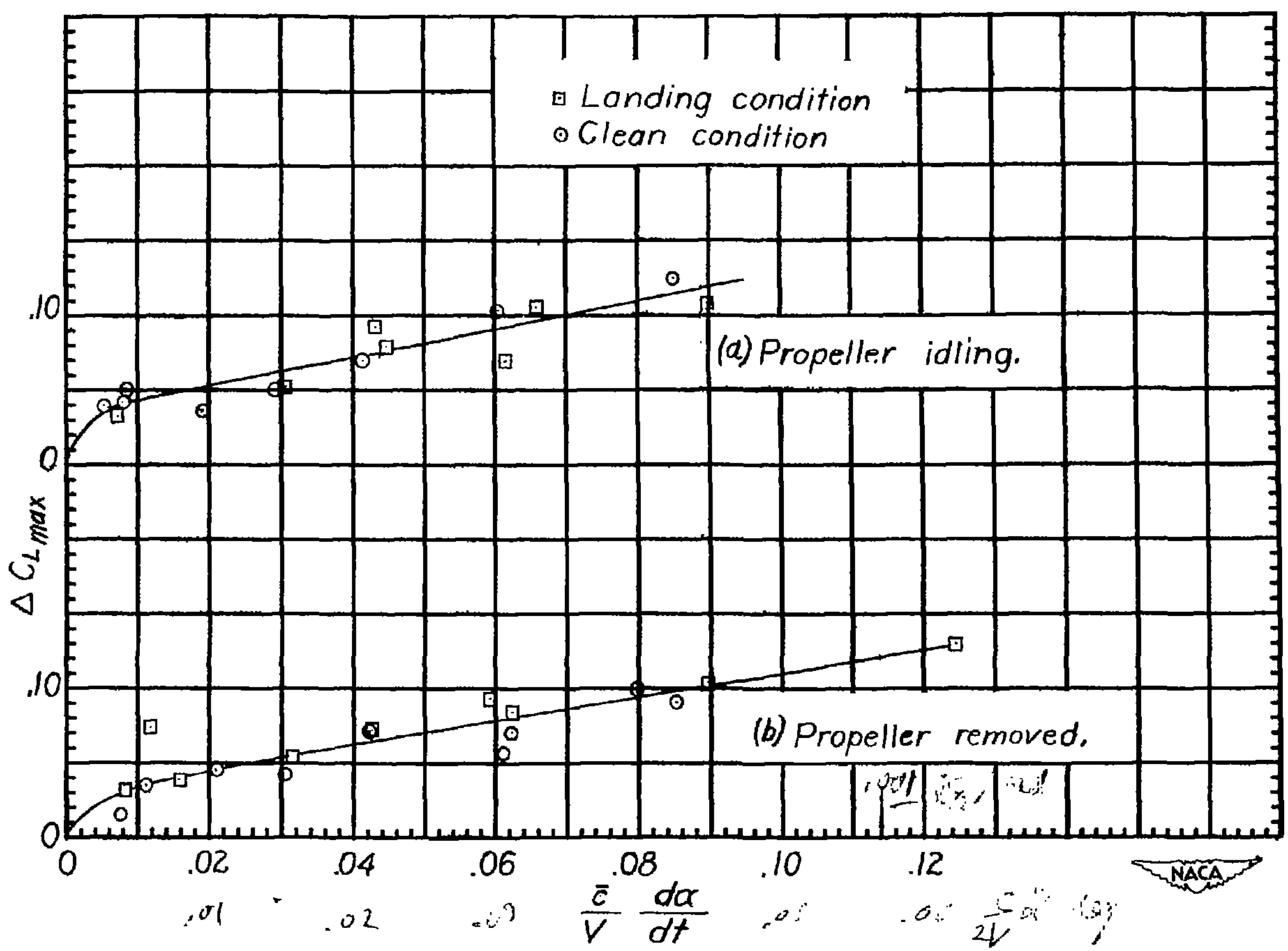


Figure 5.- Maximum-lift-coefficient increment due to $\frac{\bar{c}}{V}\frac{d\alpha}{dt}$.

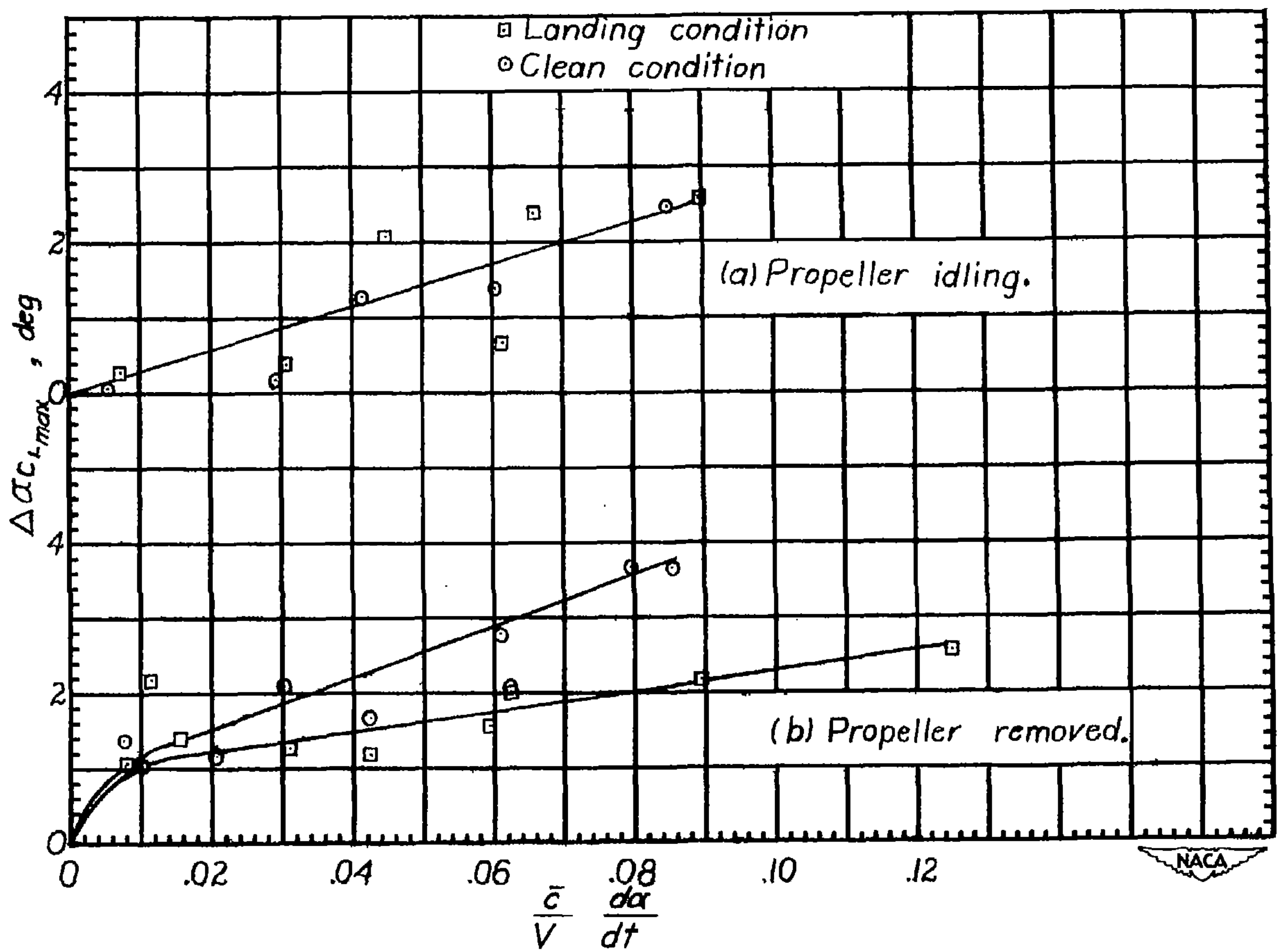
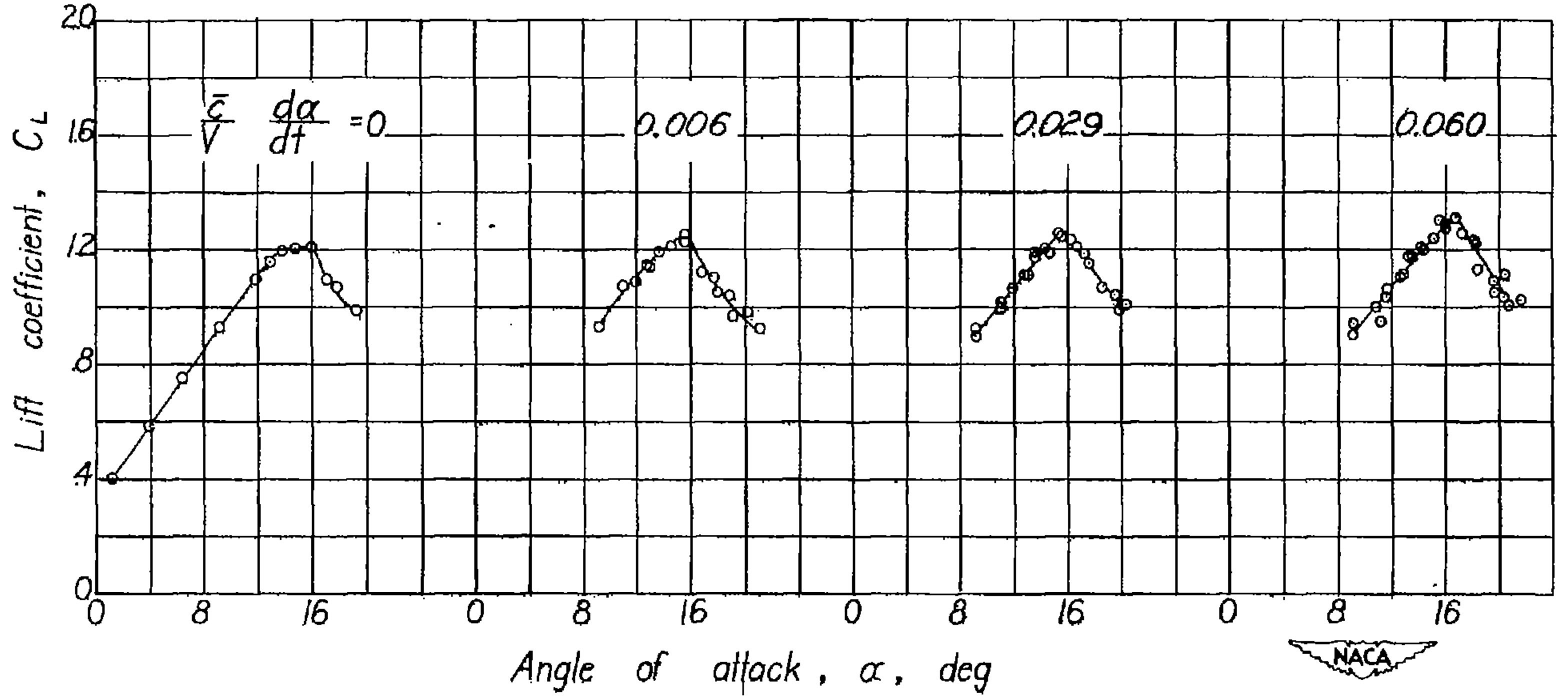
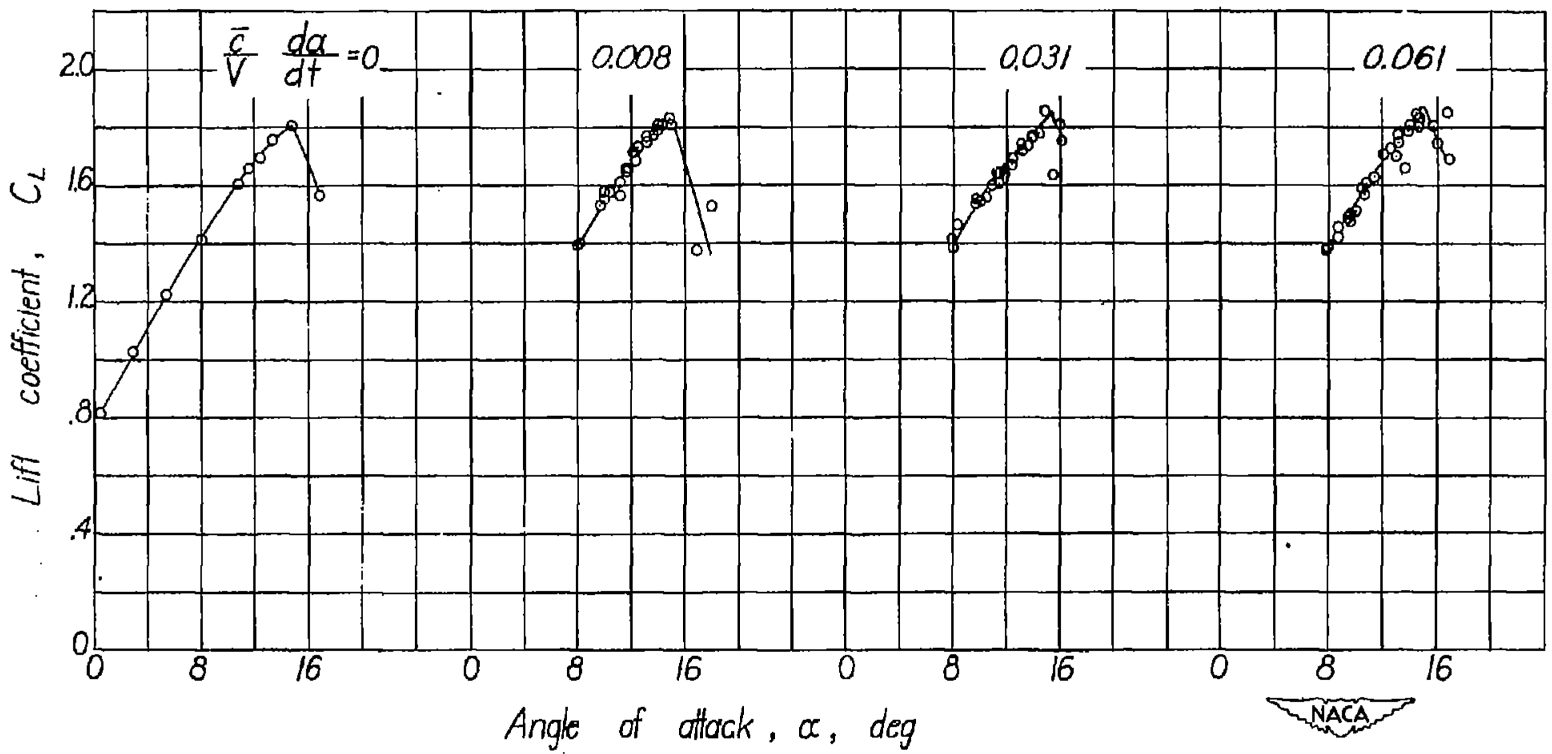


Figure 6.- Increment in angle of attack at maximum lift coefficient due to $\frac{\bar{c}}{V}\frac{d\alpha}{dt}$.



(a) Flaps and landing gear retracted; canopy closed.

Figure 7.- Effect of $\frac{\bar{c}}{V} \frac{d\alpha}{dt}$ on the lift characteristics of the fighter-type airplane. Propeller idling; airspeed, 73 miles per hour; $\frac{V}{nD} = 1.40$.



(b) Flaps and landing gear extended; canopy open.

Figure 7.- Concluded.

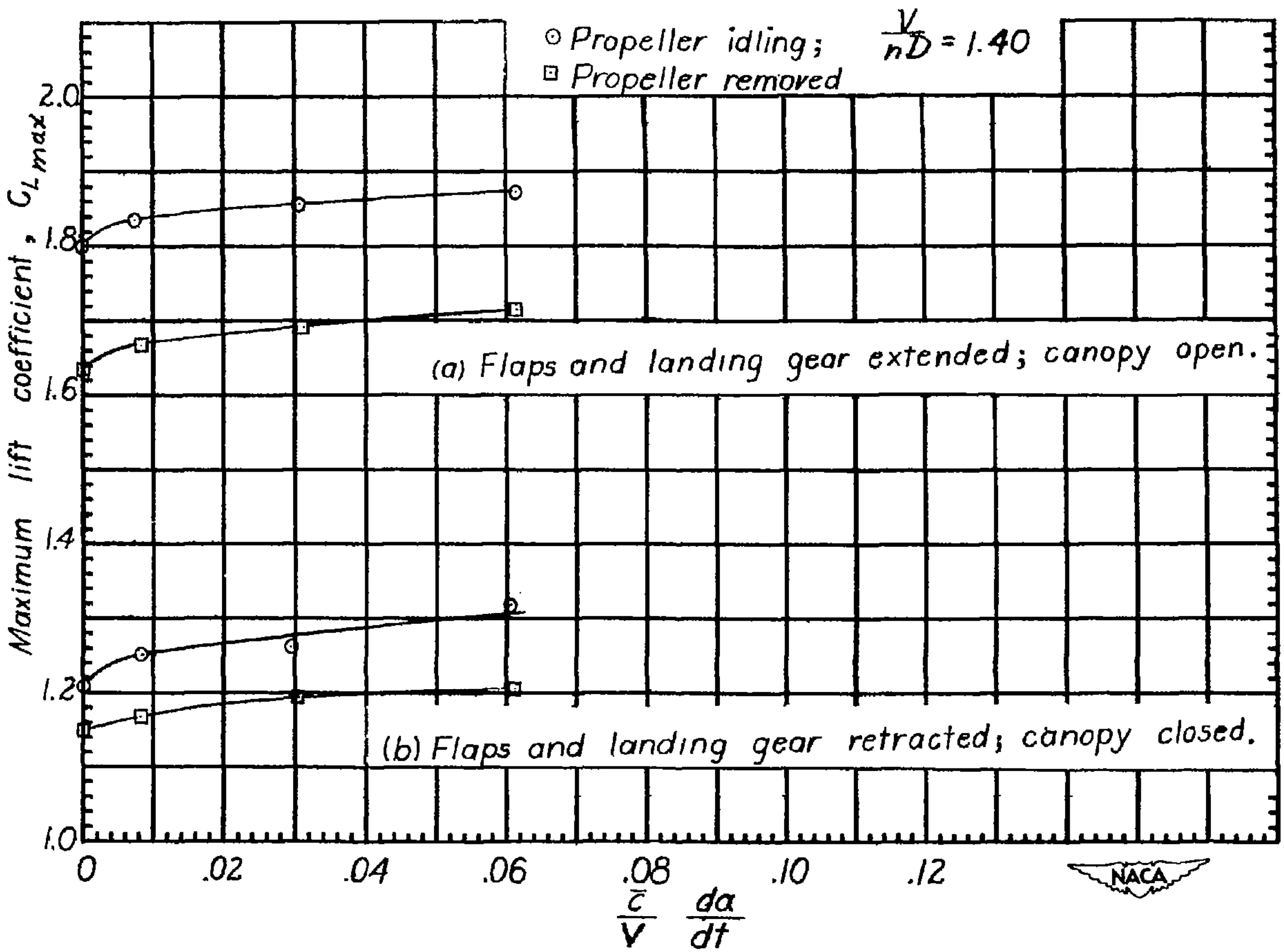


Figure 8.- Effect of idling propeller on maximum lift coefficient. Fighter-type airplane; airspeed, 73 miles per hour.

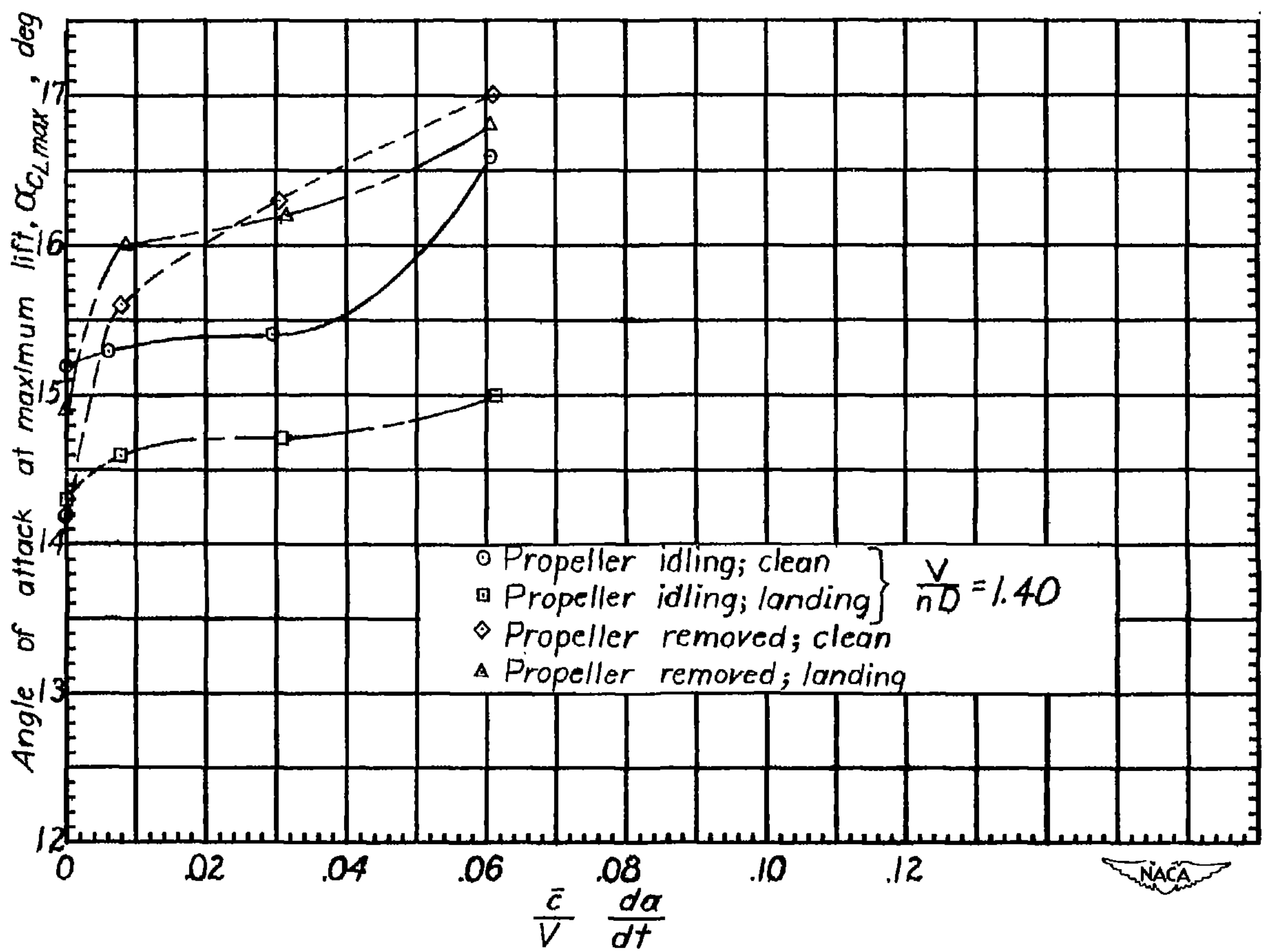


Figure 9.- Effect of idling propeller on angle of attack at maximum lift. Fighter-type airplane; airspeed, 73 miles per hour.

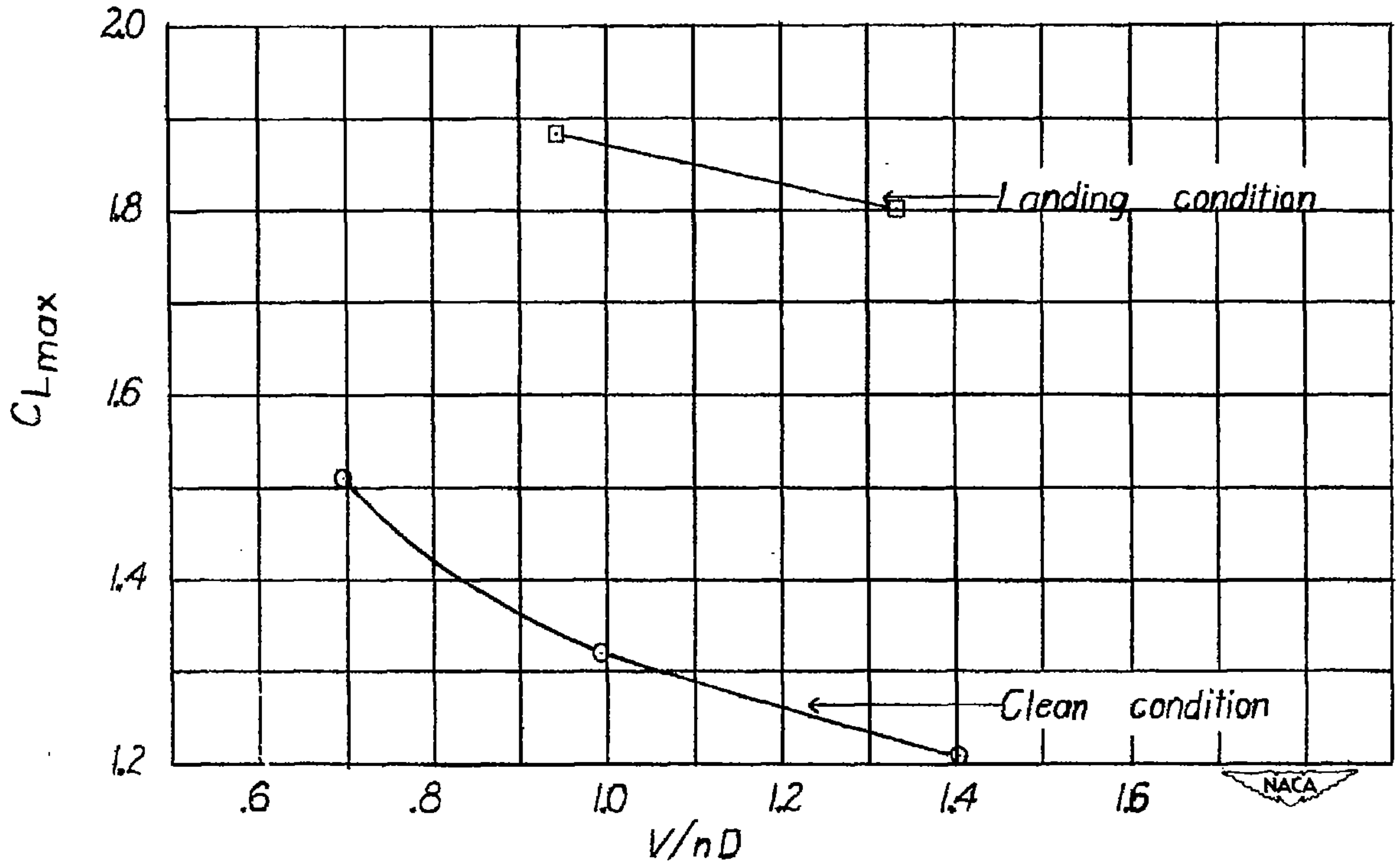


Figure 10.- Effect of propeller operation on the maximum lift coefficient. $\frac{d\alpha}{dt} = 0.$

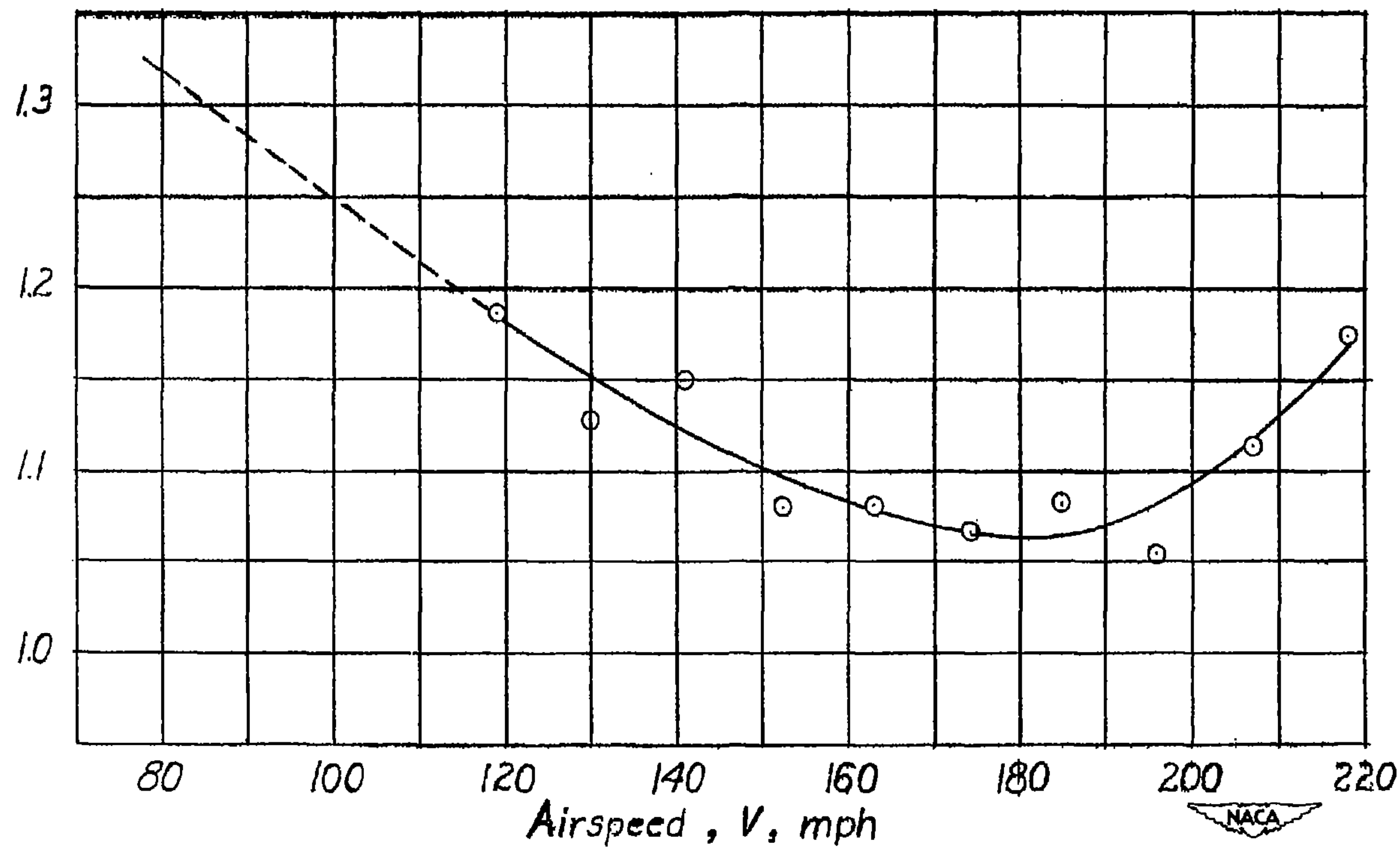


Figure 11.- Variation of propeller advance ratio with glide velocity as determined in flight tests. Engine idling; fighter-type airplane.

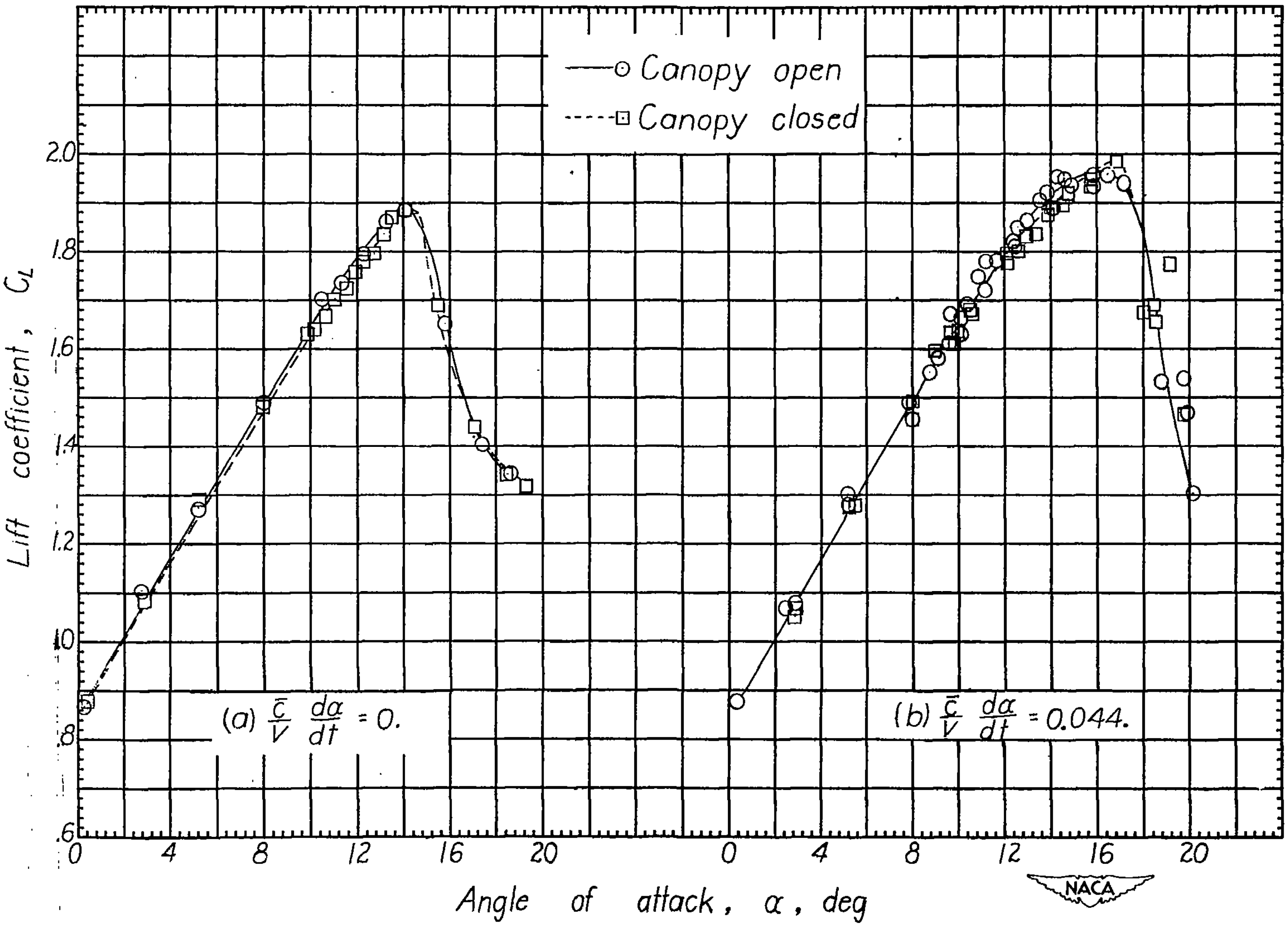


Figure 12.- Effect of the canopy position on maximum lift coefficient. Fighter-type airplane; flaps and landing gear extended; propeller idling; airspeed, 50 miles per hour.

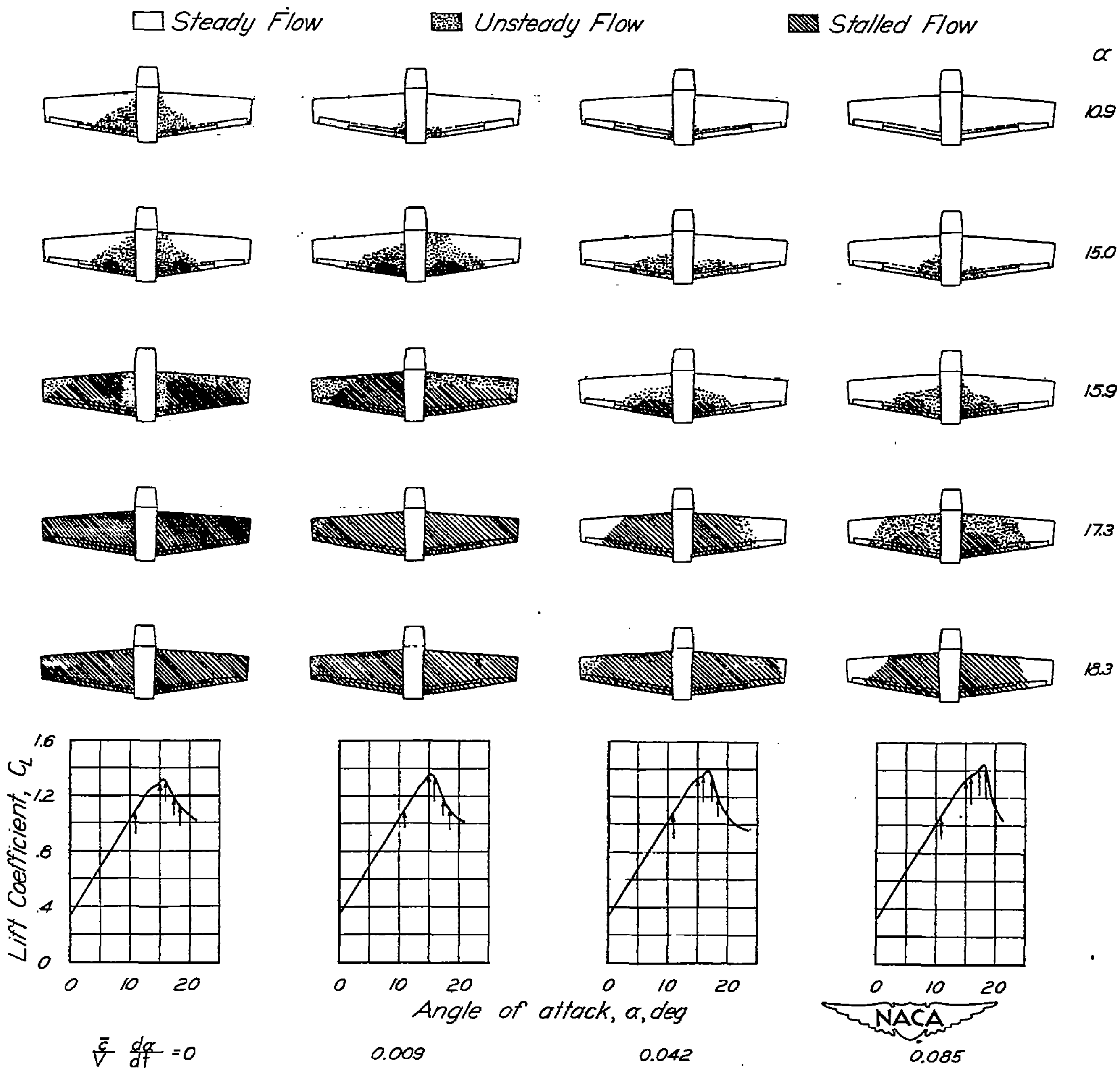


Figure 13.- Effect of time rate of change of angle of attack on the stall progression and maximum lift of the fighter-type airplane. Flaps and landing gear retracted; propeller idling; approximate $\frac{V}{nD}$, 1.05; canopy closed; approximate test velocity, 55 miles per hour.

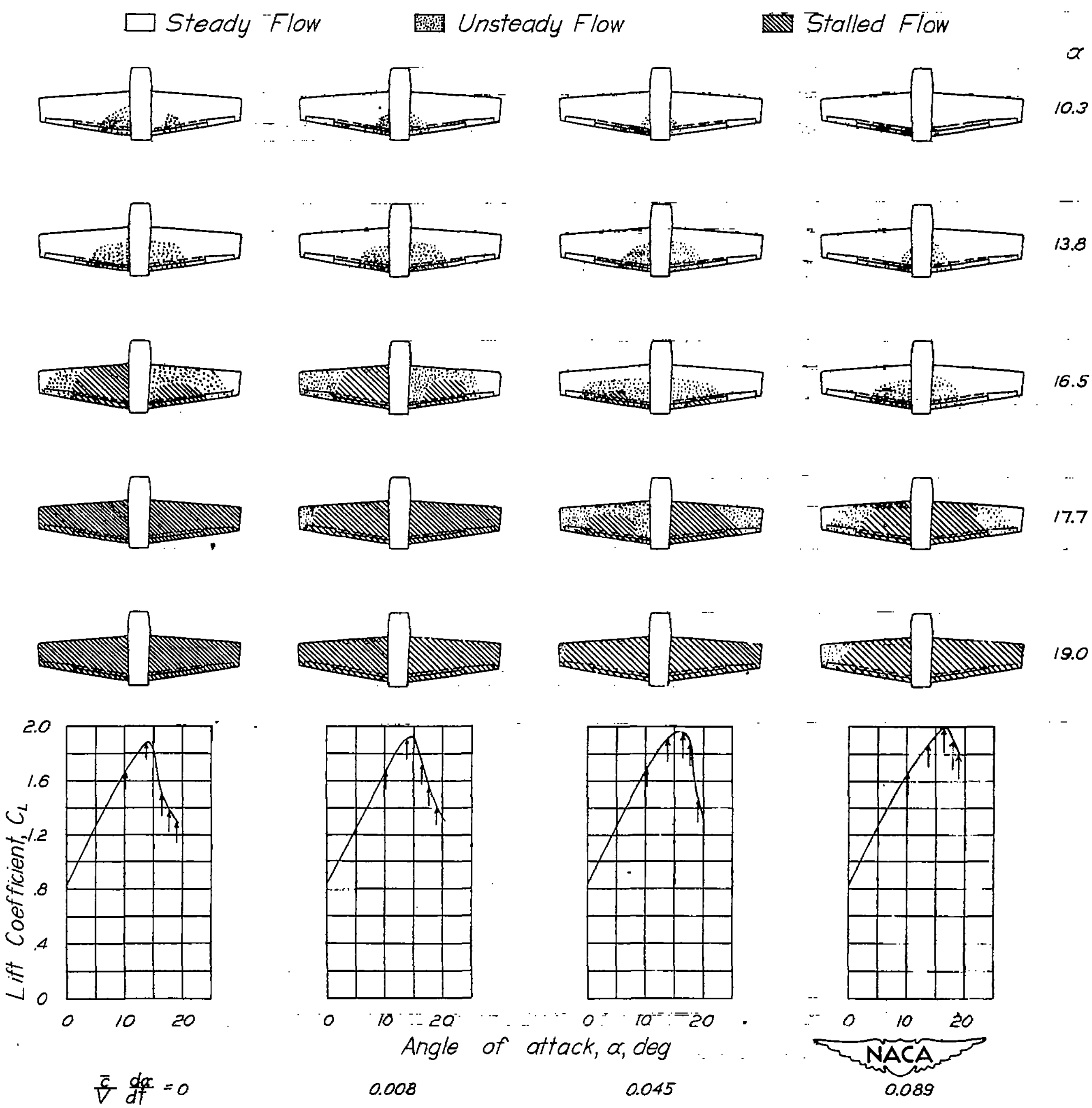


Figure 14.- Effect of time rate of change of angle of attack on the stall progression and maximum lift of the fighter-type airplane. Flaps and landing gear extended; propeller idling; approximate $\frac{V}{nD}$, 0.97; canopy open; approximate test velocity, 50 miles per hour.

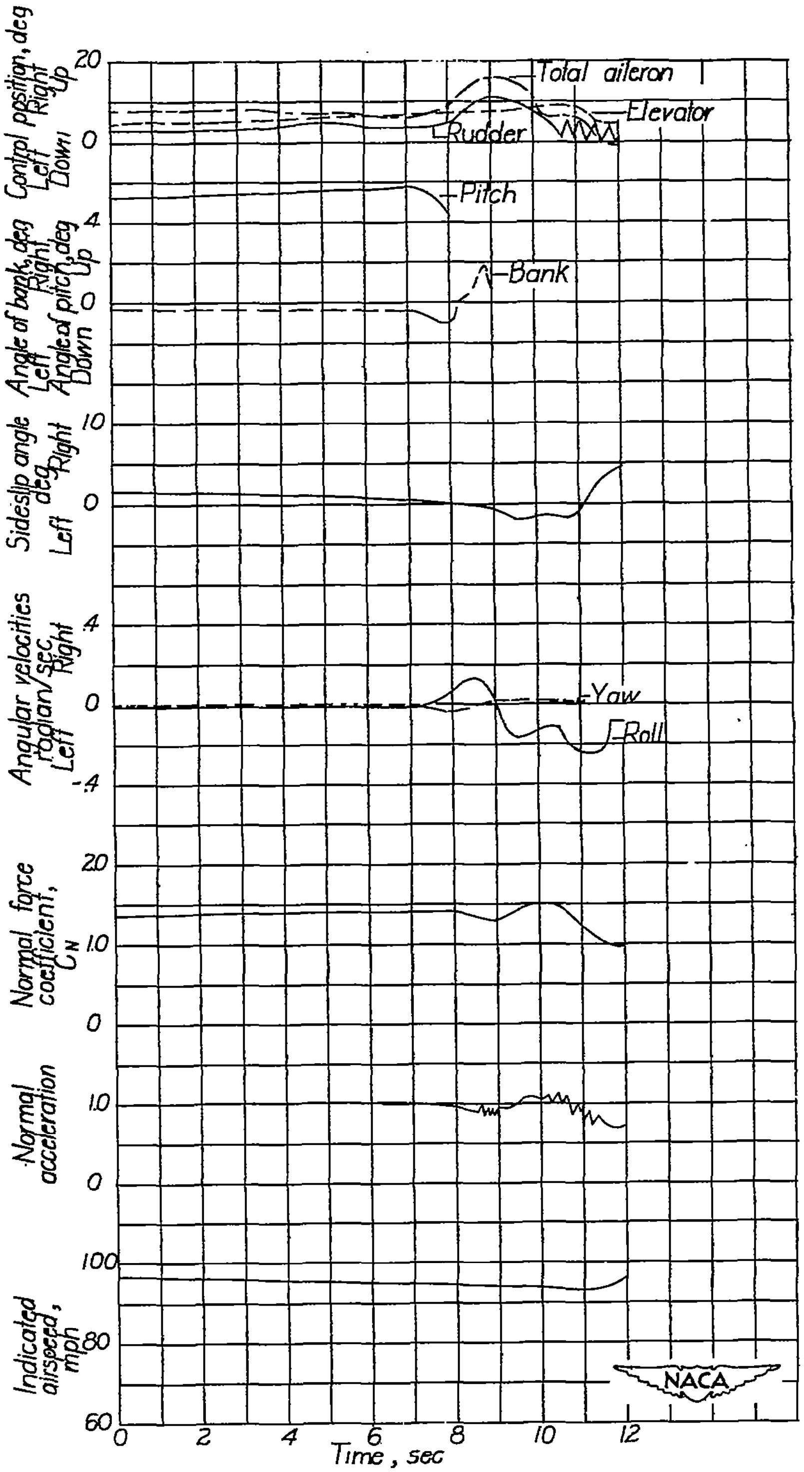


Figure 15.- Typical time history of a stall. Fighter-type airplane. Gear and flaps up; canopy closed; propeller idling; altitude, 7000 feet.

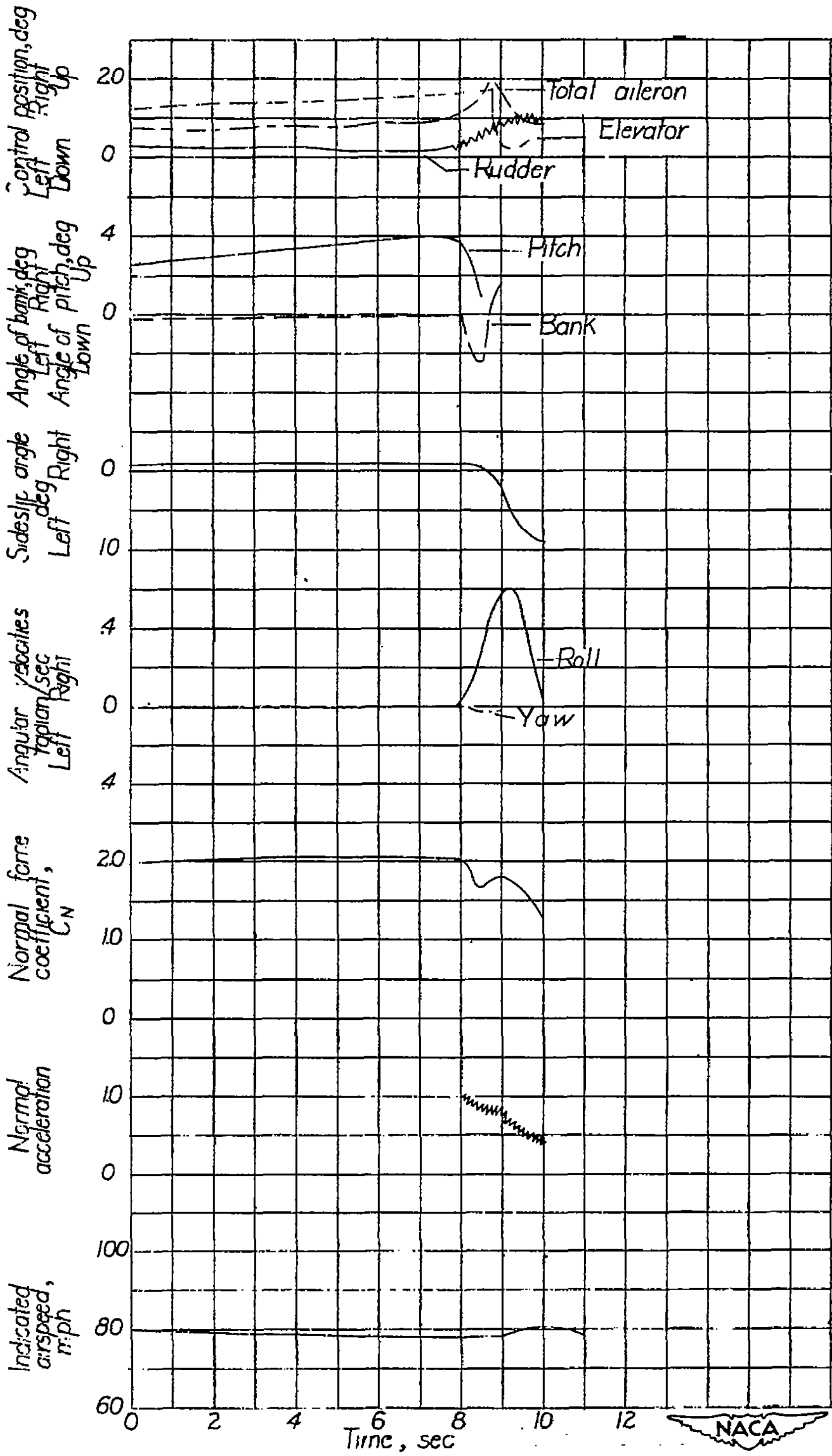


Figure 16.- Typical time history of a stall. Fighter-type airplane. Gear and flaps down; canopy open; propeller idling; altitude, 7000 feet.